Neutron Stars and Black Holes as MACHOs

Aparna Venkatesan, Angela V. Olinto, and James W. Truran
Department of Astronomy and Astrophysics, and Enrico Fermi Institute,
University of Chicago, 5640 S. Ellis Ave, Chicago, IL 60637

ABSTRACT

We consider the contribution of neutron stars and black holes to the dynamical mass of galactic halos. In particular, we show that if these compact objects were produced by an early generation of stars with initial metallicity $\lesssim 10^{-4} Z_{\odot}$, they can contribute at most 30–40% of the Galactic halo mass without creating supersolar levels of enrichment. We show that the case for halo neutron stars and black holes cannot be rejected on metal overproduction arguments alone, due to the critical factor of the choice of progenitor metallicity in determining the yields. We show that this scenario satisfies observational constraints, similar to but no more severe than those faced by halo white dwarfs. We also discuss the recent results on halo microlensing, the presence of enriched hot gas in clusters and groups of galaxies, and other observations. If there are halo neutron stars and black holes, they will be detected by microlensing experiments in the future as longer-timescale events.

1. Introduction

Studies of the rotation curves of spiral galaxies and the dynamical behaviour of galaxy clusters have shown that most of the matter in our Universe is invisible. Although most of the dark matter is believed to be non-baryonic, a significant component must be baryonic (see, e.g., Copi, Schramm & Turner 1995). One particular class of baryonic dark matter candidates consists of objects from about planetary masses to several solar masses, collectively called MACHOs (massive compact halo objects). In the last few years, several experiments have used the gravitational microlensing of stars in the Magellanic Clouds and in our Galaxy to constrain the nature and amount of such MACHOs in the Galactic halo.

These experiments have had surprising results. Brown dwarfs, which were natural candidates for subluminous MACHOs, do not form a significant fraction of the Galactic halo. In fact, MACHOs in the mass range 10^{-7} – 0.02 $M_{\odot}$ make up less than 20% of our halo's dark matter (Renault et al. 1997). Star counts from the Hubble Deep Field

(HDF) along with microlensing results are consistent with negligible halo dark matter contributions from substellar objects such as brown dwarfs (see, e.g., Chabrier & Méra 1997). Furthermore, the MACHO collaboration observed the microlensing of stars in the direction of the Large Magellanic Cloud (LMC) by objects which, based on their two-year data of eight microlensing events, have a most probable mass of about $0.5^{+0.3}_{-0.2}$ $M_\odot$ (Alcock et al. 1997). If these objects are in our halo, they could comprise about half of the halo's mass, based on a comparison with the optical depth associated with an all-MACHO halo.

Thus, there are now at least two Galactic dark matter problems: the nature of halo MACHOs which are detected through microlensing, and the composition of the remainder of the dark halo. The nature of the observed MACHOs is not yet resolved. There are competing interpretations for the microlensing data, ranging from non-baryonic halo objects such as primordial black holes to stellar contributions from a Galactic component such as the thick disk or spheroid, or from the warping and flaring of the Galactic disk towards the LMC (Bennett 1998, and references therein). Other models make a case for non-Galactic lenses, such as microlensing by stars in the LMC or SMC themselves (self-lensing), or an intervening component between the Galaxy and the LMC, such as a dwarf galaxy or a tidal tail from the LMC. At present, no model gives a compelling explanation for all aspects of the MACHO problem.

In this paper, we consider baryonic objects as one possible solution for the MACHO dark matter problem. The most likely experimental MACHO mass at present is about 0.5 $M_\odot$, which is too high for typical brown dwarf masses as hydrogen burning starts at ~ 0.08 $M_\odot$. 0.5 $M_\odot$ suggests the presence of white dwarfs (WDs) (Adams & Laughlin 1996; Fields, Mathews & Schramm 1997). Alternative candidates for baryonic MACHOs are neutron stars (NSs), and low-mass black holes (LMBHs).

Models of WD-dominated halos experience several difficulties. WD progenitors (taken to be of typical mass 2–4 $M_\odot$ in previous work) produce large amounts of enriched gas, which must be ejected by some mechanism into the intragroup medium as such gas is not seen in the Galaxy today. Since neither WD progenitors nor planetary nebulae have sufficient kinetic energy in their winds to expel the enriched gas, the presence of supernovae (SNe) from the death of massive stars (which produce NSs and BHs) is necessary. In addition, the lack of the signature expected from the early luminous phase of WD progenitors in deep galaxy surveys constrains the WD fraction in galaxy halos today to be less than 10% (Charlot & Silk 1995). Further constraints on a WD component to the Galactic halo come from searches for faint stellar objects in the Hubble Deep Field, down to $I = 26.3$ (Flynn, Gould & Bahcall 1996), and from studying the luminosity evolution and cooling history of WDs (Graff, Laughlin & Freese 1998).

Furthermore, given that roughly half of Population I stars are in binaries, a significant fraction of a WD-dominated halo could plausibly be in binary systems. These would generate, through WD-WD mergers, a larger rate of Type Ia SNe than is observed (Smecker & Wyse 1991). The chemical enrichment in ^{56}Fe from Type Ia SNe would reach far above solar values since the timescales for Type Ia SNe exceed greatly the initial period of enhanced star formation, which prevents prompt mixing and dilution of the ejecta on large scales. These SNe also do not leave remnants that could lock up the created heavy elements permanently (Smecker & Wyse 1991).

NSs and BHs from Type II SNe avoid these difficulties. Type II SNe occur over much shorter timescales, than do Type Ia, and they leave a significant fraction of their synthesized heavy elements in the NS or BH remnants. In addition, the abundance ratios of the hot X-ray emitting gas seen in clusters of galaxies (Mushotzky et al. 1996) appear to favor a Type II, rather than Type Ia, SN origin, though this is subject to some debate (e.g., Ishimaru & Arimoto 1997). Lastly, theoretical work (Woosley & Timmes 1996) indicates that an early generation of massive stars in the Galaxy could indeed have generated a large number of LMBHs through Type II and Ib SNe explosions.

Models with halo NSs and LMBHs face at least two challenges. The most likely MACHO mass as reported by Alcock et al. (1997) is lower than the typical masses of NSs (~ 1.4 M$_\odot$) and LMBHs (1.5 to several M$_\odot$). We address this point in the discussion section, but note here that the first year's data from the EROS2 (Expérience de Recherche d'Objets Sombres) experiment (Palanque-Delabrouille et al. 1998) may indicate higher MACHO masses. Secondly, the massive stars that could create NSs and BHs eject large amounts of enriched material when they become SNe, which may contaminate the interstellar medium with ^{4}He and heavy elements beyond solar values.

In this paper, we focus on the latter challenge, and show that the case for a halo with significant mass fractions in NSs and BHs is not easily dismissed from arguments based solely on excessive pollution from the ejecta of the SNe creating these objects. This conclusion is contrary to previous work (see, e.g. Ryu, Olive & Silk 1990), primarily because we use recent results from Woosley & Weaver (1995; henceforth WW95) for the nucleosynthetic yields from the evolution of massive stars of low metallicity that explode as Type II SNe. These stars do not have the prohibitively high metal yields that are associated with solar metallicity progenitors. Our goal here is to show that this is therefore not *prima facie* evidence to reject halo NSs and BHs, and to place an upper limit on their contribution, given the greatest viable stretch of parameters. Though this scenario is not free of assumptions (§ 2), we show that this upper limit is consistent with other related constraints.

In order to maximize the contribution of NSs and LMBHs to the halo dark matter, we focus on an initial burst involving only high-mass stars and calculate the yields from just this epoch. This early generation of massive stars create a large population of compact objects in the initial phase of the formation and evolution of the Galaxy. The generated remnants are mostly NSs and LMBHs, with some heavier black holes. The fraction of NSs relative to BHs depends on the maximum mass of NSs; LMBHs could have masses as low as 1.5 $M_\odot$ (Brown & Bethe 1994).

The plan of this paper is as follows: In § 2, we discuss in detail the assumptions that we make for a scenario that creates halo NSs and BHs. In § 3, we compute the yields in hydrogen, ^{4}He, and metals generated by the SNe from this early population. We derive a maximum mass fraction in the halo made of remnants from these stars, for three cases of initial metallicity of the progenitor. We then calculate the mass of gas required initially for the Local Group to dilute the final abundances of ^{4}He or metals in the leftover gas to solar values. In § 4, we discuss some implications of this scenario, relevant constraints, and some recent observations. We then conclude in § 5.

2. A Possible NS/BH Scenario

A halo with a significant fraction of its mass in stellar remnants must meet certain constraints of mass and metallicity. The stars that create NSs and BHs also leave behind ejecta whose enrichment is above solar values, and whose mass exceeds that in the remnants and therefore those of the present Galactic disk and bulge. A scenario that proposes NSs and BHs as significant contributors to halo dark matter must necessarily invoke at least the following assumptions. A starburst that selectively forms only massive stars, and in which most of the baryons participate, is required. Furthermore, this burst must occur sufficiently early in the Universe's history, as such a bright phase is not seen at lower redshifts. The prompt recycling of stellar debris that occurs in standard chemical evolution is not desirable for a NS/BH scenario, as stars in present galaxies show a large spread in metallicities and presumably reflect enrichment from generations subsequent to any proposed early starburst. Therefore, some mechanism is needed that removes the initially metal-rich ejecta and that could aid any dilution that ensues, such as winds or outflows from the star-forming regions. We discuss these chosen assumptions below; we will see in §3 that low-Z stars alleviate any dilution constraint, compared with high-Z stars.

We assume a dynamical mass of 10^{12} $M_\odot$ for a halo of radius 100 kpc (see, e.g., Peebles 1995, plus the assumption that $\rho_{\rm halo} \sim r^{-2}$). Microlensing experiments constrain the optical depth along the line of sight in MACHOs from a lensing event, which gives a direct estimate

of the total mass in MACHOs. To extend this to a halo baryonic fraction, we need to divide this by the total mass of the halo, which is uncertain and dependent on specific models and assumptions. In the results of the MACHO experiment, according to Alcock et al. (1997) and Griest (1997), the halo mass fraction of MACHOs can take values between 10% and 100% for different halo models, excluding experimental error; however, the most likely total mass in halo MACHOs within 50 kpc has been very stable at about 2 $\times 10^{11}$ $M_\odot$. Keeping these considerations in mind, we derive first the maximum masses in halo MACHOs in NSs and LMBHs, which we can extend to their halo mass fraction.

In this work, we concentrate on the Local Group (LG) when deriving limits from specific constraints. We assume that the two most luminous, dominant spiral galaxies in the LG, the Milky Way and M31, each processed $\sim 10^{12}$ $M_\odot$ of primordial gas through an early generation of massive stars. This first generation was made of very low metallicity ($\ll Z_\odot$) gas, which cools inefficiently and could favor the formation of higher stellar masses (Adams & Laughlin 1997). Furthermore, the maximum stellar mass that is stable increases with decreasing metallicity. One can approximate this maximum mass as (Adams & Laughlin 1997): $M_{*,max} \approx 114$ $M_\odot$ $(1 - 2.4Z)^2$, which is approximately 114 $M_\odot$ for very small Z. From these arguments, we take a range of progenitor masses 10–100 $M_\odot$, which create NSs and BHs through Type II SNe. We consider only stars of masses above 10 $M_\odot$ to maximize the number of NSs and LMBHs, and assume a Salpeter initial mass function (IMF), where the number of stars born per unit mass interval, $\xi(M) \propto M^{-2.35}$. Although the present-day disk IMF is biased towards low-mass stars, there is evidence for significant high-mass star activity in the past. One possible explanation is a bimodal star formation history, involving early IMFs skewed towards high-mass stars (Elbaz, Arnaud & Vangioni-Flam 1995; Fields, Mathews & Schramm 1997). Elbaz et al. (1995) point out that observations of starburst galaxies, in which the star formation activity and the relative number of massive stars appear related, suggest a truncated IMF.

As we show in this work, the composition of the progenitor star strongly determines that of its ejecta, particularly the ejecta's metal content. The lower the metallicity of a star, the weaker is its pollution of the surrounding gas when it becomes a SN, and the higher the mass of the remnant. Thus, a $Z = 0$ star is the most favorable for creating galactic halos with a significant fraction in NS/BH remnants. However, self-enrichment of star-forming regions leads eventually to stars of higher metallicities. This problem is less serious if the timescale for the early massive star formation is short compared to the mixing timescale for the star-forming regions. We will therefore assume a burst approximation, i.e., there is no immediate recycling of stellar ejecta as in standard chemical evolution. The redshift at which such a burst occurred can be constrained by background light limits measured today; this is derived in §4.

The star formation characteristic of the present epoch, where the rates of SNe are much lower and whose ejecta are mostly incorporated into new generations of stars, begins later in the Universe's history. The Galactic disk and halo stars are not formed in our treatment explicitly; we assume that the baryons that form such Pop. I and II stars are not enriched by the earlier starburst, or Pop. III, phase. Such a segregation could occur if galactic winds accompanying the burst phase removed associated polluted ejecta, leaving a fraction of material behind that eventually goes into Pop. I/II stars. As Pop. II stars have a mean metallicity of about 1/30 $Z_{\odot}$, this segregation of the material forming baryonic MACHOs from that forming disk and halo stars must be efficient, and is essential to the scenario discussed here.

In contrast to the case of Pop. I/II stars, the hot X-ray gas that is seen in many clusters and groups of galaxies contains a significant fraction, if not most, of the baryons in these systems, and is enriched in metals to about $Z_X \sim 0.3 Z_{\odot}$, with some cases approaching solar values (see, e.g. Mulchaey et al. 1996, Mushotzky et al. 1996). In this work, we will use this general constraint from studies of this X-ray gas, rather than the range of observed abundances in Pop. I and II stars, as we are interested in the remnants from a stellar phase that involved the bulk of the baryons. We take the degree of enrichment in intracluster and intragroup gas in other systems to be roughly solar in metals. As the enriched X-ray gas exists in systems that also have galaxies containing low-Z stars, a fair fraction of the baryons in such systems may well have undergone stellar processing separately from the galaxies' present stars, similar to what we have postulated here. We discuss in §4 how the self-enrichment of disks can be distinct from any early starburst phase. Note further that the combined baryonic mass in the Galactic disk and halo stars is at most a few percent of the total baryons associated with the Galaxy in its burst phase, and will not alter the main conclusions of this paper.

In the next section, we use the results of WW95 for the integrated yield from the early generations of massive stars. We assume that the SNe associated with this early stellar phase can effectively drive winds. Two outcomes are possible: the winds could remove the metal-rich ejecta from the protogalactic regions and then from the LG itself, or they could mix the polluted ejecta with the ambient primordial gas outside early star-forming regions. The second option has the potential to constrain the mass of baryons that participate in an early burst, and the final mass in remnants, given a dilution criterion. We do this for the LG in §3, where we derive the baryonic mass required to form the LG in order to avoid supersolar ^{4}He or metal values in the diluted gas remaining after the first epoch of stellar processing. This provides a reasonable upper limit to the contribution of halo NSs and BHs in the extreme case of retaining all the enriched ejecta, i.e., no mass loss. We choose solar values as an average final LG metallicity for the reasons discussed above; though ^{4}He

abundances are not measured in the X-ray gas, we include this case as we will see that ^{4}He is more constraining than metals, as far as dilution requirements are concerned for low-Z massive stars' ejecta. Note that if mass loss from the LG does occur and the enriched undiluted gas is ejected through galactic winds and outflows, abundances in the leftover gas can more easily remain at subsolar values. We do not consider this explicitly in this work, as this would necessitate further assumptions on the nature, mass and metallicity of the intergalactic medium.

Finally, we consider the *total* mass in NSs and BHs. The actual fraction of NSs versus BHs depends on the uncertain maximum mass of NSs. Some authors have recently argued that stars of masses in the range 18–30 $M_\odot$ could leave remnant LMBHs after exploding as Type II SNe (Brown & Bethe 1994; Woosley & Timmes 1996). LMBHs may be formed when the mass of a remnant compact object exceeds 1.5 $M_\odot$ (Brown & Bethe 1994). Also, observations may indicate an upper limit to the NS mass of 1.5 $M_\odot$ (Brown, Weingartner & Wijers 1995). Finally, simulations of Type II SNe (WW95; Timmes, Woosley & Weaver 1996) of low-metallicity stars ($Z \leq 10^{-4} Z_\odot$) with masses above $\sim$ 15 $M_\odot$ show that their remnants have masses that exceed 1.5 $M_\odot$. We therefore derive a minimum mass fraction in NSs by assuming that the smallest progenitor mass for a LMBH is about 15 $M_\odot$. If NSs can have masses above $\sim$ 1.5–2 $M_\odot$, the halo remnants in our results would have fewer BHs.

3. Results

In this section, we calculate the IMF-integrated yields for a burst involving only massive stars of very low Z, as described in §2, and for $Z = Z_\odot$ stars for comparison. We show that the enrichment increases with the progenitor's metallicity, with $Z = Z_\odot$ stars resulting in the familiar extreme metal pollution, and $Z = 0$ stars having the least enriched ejecta and the highest mass left in remnants. We then derive the baryonic requirement for the LG, given the scenario described in §2, for dilution of the ejecta from such an early phase to solar values in ^{4}He or metals. Interestingly, the dilution requirement for ^{4}He is more stringent than that for metals.

We use WW95 to calculate the yields for the range of high–mass stars ($10 \leq M/M_\odot \leq 100$) of metallicities $Z = 0$ (case 1), and $Z = 10^{-4} Z_\odot$ (case 2). We then fit the values for the ejected masses in hydrogen, ^{4}He, and metals, as well as remnant masses, as a function of the mass of the star in the range 10–40 $M_\odot$. We expect minimal mass loss effects during the main-sequence lifetimes of the low–metallicity progenitor stars, but there are significant uncertainites in the energy, location and specific type of mechanism in launching the shock that leads to SNe in stars more massive than 40 $M_\odot$. The remnants in these cases are most

likely higher-mass black holes (WW95). The role of fallback and late-time accretion makes estimating the final remnant mass and the element yield less reliable. Here we extend the mass fractions in the four quantities of interest from their values at 40 $M_\odot$ to the range 40–60 $M_\odot$. Above 60 $M_\odot$, we assume that the entire star collapses into the remnant.

In Figures 1 and 2, we show the yields of hydrogen, ^{4}He, metals and remnant masses for stars of masses 10–40 $M_\odot$ in cases 1 and 2 respectively, with various symbols and the solid lines representing the values from WW95 and a polynomial fit. Figure 1 shows a polynomial fit for the hydrogen and ^{4}He yields only. For progenitor masses above 25 or 30 $M_\odot$, a star in the tables of WW95 had more than one case of the final kinetic energy of the ejecta at infinity, with models A, B, and C having progressively larger SN shock energies. We chose the model for which this value was closest to 1.2×10^{51} ergs, i.e., model A in WW95, which had the lowest total ejected masses compared to models B or C. Clearly, the model with minimal ejecta will produce remnants with larger masses than one with maximal ejecta. Figures 1 and 2 show the remnant masses for the models with maximal ejecta as well, to illustrate the point that depending on the explosion energy, solar-mass compact objects can result from stars as massive as 40 $M_\odot$.

From the figures, we see that there is generally more variability in the yields of zero–metallicity stars (except for hydrogen), due to their poorly understood structure and evolution. We obtained good fits only for the hydrogen and ^{4}He yields in case 1, and show the ejected mass in metals and remnant masses in Figure 1 to emphasize their fluctuations. To compute metal yields in case 1 integrated over the whole IMF, we took average values for mass bins of 5 $M_\odot$ over 10–40 $M_\odot$, including separately the peak at 22 $M_\odot$; the mass left in remnants for case 1 was taken to be the difference between 10^{12} $M_\odot$ and the integrated post-supernova output in hydrogen, ^{4}He and metals. Above this mass range, we followed the procedure described earlier.

The $Z = 0$ stars have lower integrated yields in heavy elements and can create galactic halos with higher mass fractions in NSs and BHs. Table 1 shows the computed elemental yields and remnant masses in solar mass units for cases 1 and 2, resulting from a stellar population of total mass 10^{12} $M_\odot$. This is the mass processed initially by each galaxy in the Group into massive stars. Also shown are the mass fractions of ^{4}He and metals (Y and Z) in the ejected gas relative to solar values, and the fraction of the total halo mass in remnants, $f \equiv M_{\rm rem}/10^{12}$ $M_\odot$. f should be viewed as an upper limit, as the stellar remnants which are created here are assumed to eventually reside in the galactic halos that form later. For comparison, we include the case of solar metallicity progenitors (case 3) for both the minimal ejecta (mE) and maximal ejecta (ME) models from WW95. We assume $Z_\odot = 1.89 \times 10^{-2}$ and $Y_\odot = 0.275$ by mass fractions.

From these results, we see that there is more total mass in remnants, and ejected gas that is less metal-rich, for $Z = 0$ stars as compared to the $Z = 10^{-4} Z_{\odot}$ stars. For all cases, the minimum fraction of these remnants in NSs is 24%, from stars of mass 10–15 $M_{\odot}$. Though each set of progenitors shown in Table 1 has very different metal enrichment in the ejecta, $Y/Y_{\odot}$ is roughly the same for all of them.

If we require that the Galaxy and M31 have on average solar abundances or lower in ^{4}He and metals, we need to dilute the enriched ejecta from each galaxy (Table 1) with a reservoir of unprocessed gas (at the same metallicity as the progenitors for cases 1 and 2). This is done in Table 2 for two values of the primordial ^{4}He abundance: 0.232 (Copi et al. 1995), and the high value of 0.249 (Tytler, Fan & Burles 1996). The initial mass of gas needed for dilution (including the 2×10^{12} $M_{\odot}$ for the stellar processing in M31 and the Galaxy) will depend on whether we have the final $Y_{\rm gas}$ or $Z_{\rm gas}$ approach solar values. Table 2 shows the baryonic requirement for the entire LG for either purpose for cases 1 and 2, and the final enrichment in both quantities relative to solar values. The overall range of initial gas masses from which the LG formed is 2.4–8.1 $\times 10^{12}$ $M_{\odot}$.

An alternative for lowering final abundances is to invoke the loss of most of the metal-rich ejecta from the Group with time, as is done for some WD models (see, e.g., Fields et al. 1997). But we see that even without the loss of metal-rich gas, a significant Galactic halo fraction in NSs and BHs can be attained if, on average, the gas in the Group has solar metallicity. Table 2 also shows that, except for one listed case, the requirement that ^{4}He in the leftover gas be at most solar guarantees metallicities below solar. In other words, ^{4}He is *more* constraining than metals, as far as dilution requirements are concerned for massive stars' ejecta.

Table 2 illustrates the extreme metal enrichment from massive stars of solar metallicity, and how unfavorable such stars are for creating a large population of compact objects. For example, to dilute the metal-rich ejecta from case 3 stars to solar Z-values, the LG must form from primordial gas of initial mass $\gtrsim 10^{13}$ $M_{\odot}$. This is prohibitively large, compared with the corresponding 2.4 $\times 10^{12}$ $M_{\odot}$ for case 1.

Within the uncertainties in stellar structure and evolution, the case for a halo with significant mass fractions in NSs and BHs is not easily dismissed from arguments based solely on excessive contamination of the intragroup medium with heavy elements. Such arguments pose serious difficulties for higher metallicity progenitor stars such as the $Z = Z_{\odot}$ case. In contrast, NSs and BHs produced by very low metallicity massive stars can exist in the Galactic halo, without overproducing metals or ^{4}He. There are however several other issues that relate to the consequences of the formation of such halos; we proceed to address them next.

4. Discussion

We have derived halo mass fractions in NSs and BHs for the scenario described in §2, and the baryonic requirement for dilution of the ejecta to solar abundances for two cases of very metal-poor stars. As this population of compact objects is created astrophysically, this scenario is subject to several observational constraints, including Big Bang nucleosynthesis (BBN) limits on the baryon density, and background light limits. Also of relevance are measurements of the mass and metallicity of gas presently in the Galaxy, the LG and other systems, and the role played by subsequent stars in enriching the Galaxy.

First, as shown in the previous section, for the ejecta from stars that formed M31 and the Galaxy to not overenrich the ambient gas with respect to solar abundances, we need a large amount of primordial gas that was not processed through stars that could dilute the enriched ejecta. For both $Z = 10^{-4} Z_\odot$ and $Z = 0$ stars, that translated into an initial baryonic reservoir of $\sim 2 - 8 \times 10^{12}$ M$_\odot$. BBN constrains the cosmological density of baryons $\Omega_b \equiv \frac{\rho_b}{\rho_c}$ to lie in the range $0.01 \leq \Omega_b h^2 \leq 0.024$, where $h \equiv H_0$ /(100 km/sec/Mpc) (Copi et al. 1995). Here ρ_c is the critical density required to close the Universe, $\rho_c = 2\ h^2\ 10^{-29}$ g cm^{-3} $\simeq 3\ h^2 \times 10^{11}$ M$_\odot$ Mpc^{-3}; for a range of 0.4 to 1.0 for h, Ω_b can vary from 1% to 15%. Recent measurements of the primordial deuterium abundance in high-redshift quasar absorption systems have yielded $\Omega_b \simeq 0.02\ h^{-2}$ (Burles & Tytler 1998), which gives a density in baryons of $\rho_b \simeq 6 \times 10^9$ M$_\odot$ Mpc^{-3}.

Given ρ_b, and that the LG is required to have assembled from the range of initial baryonic masses in Table 2, we see that a baryon-gathering radius of $\sim$ 10 Mpc is necessary. This volume contains a baryonic mass of about 3 $\times 10^{13}$ M$_\odot$, while the dynamical (i.e. total) masses of all the groups of galaxies present in this volume, including the LG, is estimated at about 8 $\times$ 10^{13} M$_\odot$ (Tully 1987). We assume that there is no relative baryon concentration in the LG, i.e., the LG will receive some fraction of the baryons in the 10 Mpc-radius volume, depending on the estimates for the LG's total mass. Such a partitioning will not be in conflict with the existence of field galaxies or groups around us, and it can then be compared to the requirements for dilution from Table 2.

One measurement of the dynamical mass of the LG, based on the least action principle (LAP), gives $M_{\rm LG} \sim 6 \times 10^{12}$ M$_\odot$ (see, e.g., Peebles 1993). This is 8% of the dynamical mass in galaxies in the volume of radius 10 Mpc and gives the LG about 2 $\times 10^{12}$ M$_\odot$ in baryons, which is close to the lowest mass in Table 2. In this case, only the $Z = 0$ progenitors which have $Z_{\rm gas,f} = Z_\odot$ are permitted, and even then just barely. In another analysis involving the LAP, Dunn & Laflamme (1993) find that $M_{\rm LG} \sim 2.2 \times 10^{13}$ M$_\odot$. For this mass, the LG has 28% of the dynamical mass in the galaxies in a volume of radius 10 Mpc, and thus receives just over 8 $\times 10^{12}$ M$_\odot$ in baryons. This number is approximately equal to the highest mass

in Table 2 and roughly all the cases in Table 2 are permitted. Therefore, if we require the LG to have assembled from the range of initial baryonic masses in Table 2, at least two cases are not in conflict with the existence of field galaxies or groups in a volume of radius up to 10 Mpc.

There may be a large amount of unprocessed gas (mostly hydrogen) and/or processed gas from early phases of star formation in the intragroup medium today. Depending on how much primordial gas mixed with the ejecta of early stars or became locked in later stellar generations, the present gas content of the LG could be about a few times $10^{11} - 10^{12}$ M$_{\odot}$ (Table 2). Gas remaining from forming the Group may not have been completely retained if the gravitational potential of the LG is insufficient. If this gas is still present, it must be cooler than current experimental limits on soft X-ray background detections. Unfortunately, the total mass of hydrogen in the LG is not very well-known. From 21 cm observations, the Galaxy is constrained to have about 5×10^9 M$_{\odot}$ in neutral hydrogen (Henderson, Jackson & Kerr 1982). However, recent observations of high-velocity clouds (HVCs) which contain neutral hydrogen indicate that these clouds alone, assuming that they are gravitationally bound, may have a total mass of $\sim 10^{10}$–10^{11} M$_{\odot}$, depending on the amount of dark matter that exists in the Galaxy (Blitz 1997). The fraction of the intragroup medium represented in the HVCs is more uncertain, but it is possible that these clouds are all that is left today of the initial gaseous reservoir that formed the LG.

In this work, we assume that an early phase of star formation is widespread, with efficient mixing occuring outside the star-forming regions, ensured by the effects of heating and winds from SNe. Observations of present starburst galaxies do show that they can drive large-scale winds which do not necessarily diminish the ongoing massive star formation (Heckman, Armus & Miley 1987). Therefore, for the LG, we expect any leftover gas, *if* it has remained trapped in the Group potential, to be distributed in the intragroup medium, and to have cooled to $10^5 - 10^6$ K. The upper limit is set by constraints from diffuse soft X-ray emission and the lower limit by the absorption features expected from any large amount of neutral hydrogen in the LG, which are not seen. In this temperature range, the intragroup medium is least constrained at 10^6 K by specific emission features such as O VI, as compared to $\sim 10^5$ K where the hydrogen column density is limited to $\sim 10^{17}$ cm^{-2}, or a mass of less than 10^9 M$_{\odot}$ over an area of 1 Mpc^2 for the LG. The presence of large amounts of intragroup gas at temperatures of about 10^6 K and with $Z \gtrsim 0.3\ Z_{\odot}$ is therefore an important target for future observations.

We now consider contributions to background light from the progenitor stars. The main-sequence lifetime of a star varies with its mass as: $\tau_{\rm MS} \sim 10^{10}\ (M_*/M_{\odot})^{-2.2}$ yr (see, e.g., Mihalas & Binney 1981). All the stars in this scenario have $M \geq 10$ M$_{\odot}$, or $\tau_{\rm MS} \lesssim 6$

$\times$ 10^7 years. The reduced opacity in low-Z stars leads to higher luminosities which may shorten the lifetime estimate even further (Adams & Laughlin 1997). We therefore expect none of these stars to be burning in the halo today. However, the luminosity from these massive stars and their deaths as SNe was very high in the past. To estimate the average luminosity from this bright phase, we can assume that the LG processed 2×10^{12} M$_\odot$ into 25 M$_\odot$ stars, the median stellar mass in our IMF. Since the stellar lifetimes for the scenario depicted here are all less than a few tens of millions of years, this epoch probably did not last for more than $\sim$ 1 Gyr. The average luminosity was then about 8×10^{46} erg/sec. The surface brightness associated with this luminosity over a protogalactic region of radius 1 Mpc, is 2×10^{-4} erg/sec/cm^2/sr. For the SNe, which are created from stars up to 60 M$_\odot$, the surface brightness produced, given the above assumptions, with $L_{\rm SN} \sim 3 \times 10^{42}$ erg/sec for 100 days, is 2×10^{-7} erg/sec/cm^2/sr. The SNe are so short-lived that a time-averaged luminosity is difficult to assign; however, because of the large amount of gas and dust present in the early stages of galaxy formation, conditions may be optically thick enough to lend credence to reprocessed fluxes that are relatively steady.

To compare these surface brightnesses to current limits on background light, we assume that the luminosity from the stars and the SNe are emitted over a wavelength range of 0.05–0.5 μm. This light will be redshifted, and for a source at redshift z, the net surface brightness (over all frequencies) is dimmed by a factor of $(1+z)^4$ (see, e.g., Peebles 1993). For light reprocessed into infrared wavelengths, we use the current limits from the FIRAS and DIRBE instruments from the COBE (Cosmic Background Explorer) satellite. FIRAS (Far Infrared Absolute Spectrometer) places a limit of 3.4 $(\lambda/400\mu m)^{-3}$ nW/m^2/sr in the 400–1000 μm range (Puget et al. 1996), or an average far infrared background of about 10^{-6} erg/sec/cm^2/sr. From Figure 3 of Kashlinsky, Mather & Odenwald (1996; references therein), a conservative value for the infrared background measured by DIRBE (Diffuse Infrared Background Experiment), after foreground subtraction, is about 10 nW/m^2/sr $\simeq 10^{-5}$ erg/sec/cm^2/sr, over wavelengths of 1.25–100 μm. Light emitted by a source in the 0.05-0.5 μm range would be redshifted into the DIRBE range for $z \gtrsim 1$; to be detected by FIRAS, such a source would have to be at extremely high redshifts, or have the stellar light undergo dust reprocessing. Comparing the surface brightness from the stellar and SNe contributions derived above with these backgrounds, we see that the light from the SNe is well below both the FIRAS and DIRBE limits, even before including the $(1+z)^4$ dimming. For the progenitor stars, sources at redshift $\gtrsim 1$ (3) would be compatible with the DIRBE (FIRAS) backgrounds. This assumes that the light comes directly to us, dimmed by $(1+z)^4$, and that dust, if present, absorbs and reradiates 100% of the source's emission; this is a reasonable upper limit to the contributions of an early epoch of intense star formation dominated by massive stars and the resulting SNe. Though the infrared

backgrounds constrain any period of initial massive star formation to satisfy $z \geq 1$ or 3, the onset of this phase could follow recombination or parallel that of galaxy formation.

We had mentioned earlier that the halo mass fraction in NSs and BHs in the Galaxy (Table 1), f, should be viewed as an upper limit as all such remnants are assumed to ultimately reside in the halos of the Galaxy and M31. One way this could happen would be if massive stars were formed in small protogalactic clumps at high redshifts and blew out their enriched ejecta through SN winds as galaxies were assembling. The clumps would later merge, leading to present halos that contain the remnants but not the gas leftover from making them. This sequence is similar to that described in Fields et al. (1997), where the bulk of the elements were formed at $z \sim 10$. Alternately, this starburst phase could occur in galaxies undergoing monolithic collapse starting at $z = 3 - 4$; the picture of an evaporating enriched hot gas component created by SNe, with remnants trapped in the largest galactic halo potentials, is still valid in the context of structure formation. In this event, dust in the host systems must be invoked as being responsible for significant extinction of this superluminous phase (see, e.g., Mushotzky et al. 1996, and references therein, for these points). After the hot ejecta have been blown out of small protogalactic clumps, or the massive protogalaxies, the gas that remains as a cold gas component could then either merge, or collapse, to form the disks of present-day spiral galaxies. The self-enrichment of this part of the Galaxy is a separate process from the earlier epoch of Type II enrichment that we consider.

In order to maximize the halo population of NSs and LMBHs, we focused on an early generation of massive stars. We assumed that a significant fraction of the baryons were processed through this early phase; however, it is clear that this scenario does not account for every baryon in our Galaxy. For instance, a small fraction of the total baryonic mass needs to form the disk of our Galaxy where low- and intermediate-mass stars play a crucial role. Observations of the present interstellar medium (ISM) in galaxies help quantify the role played by such stars in local chemical enrichment. For example, the relation between Y and Z satisfies $\Delta(Y)/\Delta(Z) \sim 4 \pm 1$ (Timmes et al. 1996). From Table 2, we see that this quantity, averaged over the two values of the primordial Y, is about 5 for case 1 and 1.7 for case 2. Case 1 is consistent with the observed value, but case 2 has a somewhat low value of $\Delta(Y)/\Delta(Z)$. Case 2 is similar to what we would expect *a priori* of the yields purely from massive stars. In general, stars of mass less than 8 $M_\odot$ produce the bulk of the helium from stellar nucleosynthesis, while stars more massive than this produce the bulk of the metals. The critical issues in connecting the ISM abundances with those in an intragroup or intergalactic medium are the assumptions made for the star formation history, and for how much early enrichment is reflected in the stars or ISM of present galaxies due to the role played by outflows and winds. Since the stars associated with late enrichment are a

small fraction of the total baryons, the gist of our conclusions should not be altered.

Other baryons we do not account for in this work are those responsible for metal-poor low-mass stars in the Galactic halo. The total mass in metal-deficient Galactic halo stars today is less than about 10^{10} $M_\odot$, which is a small fraction of the material processed through the early generations of massive stars discussed here. The primordial gas reserves are not significantly decreased in forming such metal-poor stars and those having low masses have not yet returned any material to the ISM. An understanding of the physical conditions that produced the two apparently distinct stellar populations in the Galactic disk and halo remains to be achieved.

5. Conclusions

We have shown that it is possible for halos with significant mass fractions in NSs and BHs to form in the LG without necesarrily overenriching the ambient gas relative to solar ^{4}He and/or metal abundances, if these objects were produced by an early generation of stars with initial metallicity varying between $10^{-4}Z_\odot$ and 0. In such cases, these remnants contribute at most 29% to 36% of the Galactic halo's dynamical mass (assumed here to be 10^{12} $M_\odot$). We find, within the uncertainties in stellar structure and evolution, that models for halo NSs and BHs cannot be immediately rejected on metal overproduction arguments alone, due to the critical factor of the choice of progenitor metallicity in determining the yields. The constraint of final Z-values of $Z_\odot$ for the ambient gas after dilution was motivated by the metallicities Z_X observed in the diffuse X-ray gas in galaxy clusters and groups, which are in the rough ballpark of solar. The baryonic requirements in Table 2 will scale as Z_X^{-1}, if the dilution criterion is adjusted to other values in the range of observed X-ray gas metallicities. Furthermore, though Y is not measured in this X-ray gas and is hence not a direct constraint, we found that ^{4}He is *more* constraining than metals as far as dilution requirements are concerned for low-Z massive stars' ejecta (Table 2). The more conventional picture of the extreme metal pollution from massive stars is true only for higher metallicity progenitors, such as $Z = Z_\odot$ stars (Table 1).

NSs make up at least 24% of the total mass fraction of these compact objects in the Galactic halo. LMBHs may be formed from stars as massive as 40 $M_\odot$ (WW95), as shown in Figures 1 and 2, depending on the kinetic energy chosen for launching the SN shock in high-mass stars, though we took the most conservative value for this.

The fraction of NSs and BHs in the Galaxy can be as high as the values in Table 1, by satisfying the requirement that the LG attains solar metallicity on average; a preferential

loss of high-metallicity gas to the intergalactic medium need not be invoked. The most favorable case of this ($Z_{\rm gas,f} = Z_\odot$) is for $Z = 0$ stars where $f = 36\%$ (Table 1), and $M_{\rm gas,i} = 2.4 \times 10^{12}$ M$_\odot$ (Table 2). The worst case is that of the $10^{-4}\,Z_\odot$ stars with $Y_{\rm gas,f} = Y_\odot$, where $f = 29\%$ and $M_{\rm gas,i} = 8.1 \times 10^{12}$ M$_\odot$. We emphasize that this derived f should be viewed as an upper limit, as we have assumed that all the remnants created in this scenario ultimately reside in galaxy halos till today. This assumption is plausible in the context of current structure formation scenarios (§4). However, if we were to be more democratic, and preserve, on the scale of galactic halos, the global baryon-to-*total* mass ratio, then the Galaxy and M31 would each receive a fraction $(M_{\rm gal}/M_{\rm LG})*f$ in remnants. Then, f would be reduced in the "best" and "worst" cases above to about 6% and 1% respectively.

$Z = 0$ progenitor stars have lower integrated metal yields and leave behind higher masses in remnants (Table 1), but as some self-enrichment is expected to occur in early star-forming regions, the case of $Z = 10^{-4} Z_\odot$ stars is probably more realistic. This however needs larger baryonic masses for dilution to avoid supersolar pollution, which would require a high adopted mass for the LG as derived by Dunn & Laflamme (1993). Nevertheless, it is possible, though just barely, to reconcile the baryonic requirements set by Table 2 with BBN constraints, without assuming a relative baryon concentration in the LG via cooling processes, etc. This is especially true for dilution of metal enrichment to solar levels. Other limits such as background light production are met more comfortably as shown in § 4. As we have discussed, the presence of massive stars at early epochs are favorable from some aspects, but no one stellar population can explain all the observations.

We have focused on an initial burst involving only high-mass stars in order to maximize the contribution of NSs and LMBHs to halo MACHOs, and calculated the yields from just this epoch. In doing this, we have assumed that the baryons that form Pop. I and II stars are not enriched by the burst which creates the MACHOS in this scenario and leaves behind a large amount of enriched gas. This segregation is possible if galactic winds which accompany the burst phase remove associated polluted ejecta, leaving a small fraction of material behind that eventually forms disk and halo stars. The combined Pop. I/II baryonic mass is at most a few percent of that associated with the burst phase, and will not alter the main conclusions of this paper. A similar separation in enrichment may have occured in the case of the hot X-ray gas, seen in many galaxy clusters and groups, which contains a significant fraction, and often most, of the baryons. This gas is relatively enriched in metals and co-exists with galaxies containing low-Z stars.

Though some recent observations have made a re-evaluation of baryonic dark matter candidates necessary, an unavoidable consequence of making a case for stellar remnants

as MACHOs is that they are only a fraction of the mass processed through their parent stars, and a significant amount of enriched gas will remain. Adams & Laughlin (1996) have noted this efficiency problem in creating halo WDs, and this is especially true for NSs/BHs relative to WDs. The early generations of stars leave behind significant amounts of enriched ejecta. It is possible that much of this enriched gas escaped altogether from the Group or was ejected into intergalactic space (as suggested in Adams & Laughlin 1996, and Fields et al. 1997). Here, we have shown that if we want to dilute Y or Z in the leftover gas to solar values, then the LG most likely started from a baryonic reservoir $\gtrsim 2 \times 10^{12}$ $M_\odot$ (§ 3). We have made a plausibility case for NS/BH halos that do not leave behind overenriched gas. However, the present uncertainties in supernova yields, the mass of the LG, and the primordial ^{4}He abundance could affect our results. The contribution of NS/BH remnants to galaxy halos may be smaller than those in Table 1, or the leftover intragroup gas could have lower metallicities. For progenitor metallicities $\lesssim 10^{-4} Z_\odot$, the total masses in the remnant population in our results are in the range of the experimental most likely total mass in MACHOs of $\sim 2 \times 10^{11}$ $M_\odot$, mentioned in § 2.

It is encouraging that the metal abundance of the gas remaining after this phase of early star formation is $Z \gtrsim 0.3$ $Z_\odot$, which is not in conflict with that of the intragroup gas in some groups of galaxies (Mulchaey et al. 1996). After the Group formed, a large amount of gas is left over in this scenario. If the potential of the LG can retain this gas, it must exist in a diffuse component in the intragroup medium at temperatures $\sim 10^6$ K; the Group's potential is probably insufficient to heat it to keV temperatures. This is consistent with the idea put forth by Mulchaey et al. (1996) that the intragroup medium in spiral-rich groups could have $T \sim 0.2$ keV, and remain invisible to current experiments such as ROSAT. Studies of clusters of galaxies show that there is up to several times as much mass in just the X-ray emitting gas as the mass in the galaxies (see e.g., Henry, Briel & Nulsen 1993). It remains to be seen how groups of galaxies, especially spiral-dominated ones, compare in this regard, especially if the potential of the group is not large enough to keep any gas that is present heated at keV temperatures (Mulchaey et al. 1996).

Alternatively, some of the leftover gas could be locked into faint low-mass field stars throughout the intragroup medium, or some gas may have been lost from the Group. In the latter case, the gas must remain ionized; otherwise, it would violate Gunn-Peterson constraints on the amount of intergalactic neutral hydrogen. The recent detections of $\sim 10^6$ K gas by the Extreme-Ultraviolet Explorer in the directions of the Virgo and Coma clusters might prove to be important in resolving the issue of the fate of such gas in nearby systems. In the case of Virgo (Lieu et al. 1996), this gas appears to be relatively enriched (~ 0.5 $Z_\odot$). Another key issue is whether the elemental abundance ratios in the hot gas in clusters of galaxies indicate a Type II or Ia SN origin; at present, it is undecided. If a Type

II SN origin for this gas emerges in future studies, it would certainly favor the presence of a remnant population dominated by NSs and BHs. We conclude therefore that most of the baryonic "dark matter" might be in cool ($\sim 10^6$ K) gas in the LG, but we emphasize that stellar remnants in the form of MACHOs are also a significant factor in the galactic dark matter problem.

Halo BHs are not expected to be significant sources of radiation, for typical halo ambient gas densities. However, BHs from this population have a local number density of $\sim 2 \times 10^{-5}$ pc^{-3}, assuming that they are distributed in a 100 kpc halo today. Therefore, there could be at least one such BH within a 50 pc radius from us. If it has sufficiently low velocity, it might be detected in future projects such as the Sloan Digital Sky Survey (Heckler & Kolb 1996).

As we have seen, evaluating the case for stellar remnants as MACHOs is not free of some assumptions. The IMF from which the MACHOs were created must be different from that of present galactic disks. The IMF's peak must be tailored to $\sim$ 2–4 $M_\odot$ for WDs, or to include only stars more massive than about 10 $M_\odot$ for NSs and BHs. Furthermore, all candidates face some critical issues. To not overenrich the Universe, some dilution of metal-rich SN ejecta must take place, and this constraint is considerably tighter for NS/BH remnants than for WDs, simply due to the fraction of the progenitors that collapses into the remnant in each case. If dilution does not occur, and the enriched gas is ejected from galaxies into an intracluster or intergalactic medium, strong constraints, from measured iron and oxygen abundances in the intracluster medium or from the carbon enrichment in the Lyman-alpha forest clouds (particularly for WD models), must be considered. (See Fields, Freese & Graff (1998) for a comprehensive discussion on the relative merits and limitations of these baryonic MACHO candidates.) The burst of intense star formation may be unobservable if it occurred at sufficiently high redshifts or if it is obscured by dust. However, halo WDs must contend with limits from the Hubble Deep Field, which constrains their age via their cooling emission, and, with greater model dependency, the current measured rates of Type Ia SNe, while halo NSs and BHs contribute a direct signature primarily through their mass.

The MACHO experiment's results indicate that about 50% of our halo may be made of objects of mass ~ 0.5 $M_\odot$ (for a "standard halo" mass of 4×10^{11} $M_\odot$ within 50 kpc). Experiments with longer periods of observation may detect events of longer duration. The typical MACHO mass is unlikely to be lower than the presently quoted 0.5 $M_\odot$, as strong constraints placed by the MACHO and the EROS collaborations (Renault et al. 1997; Alcock et al 1998), based on shorter timescale events, have already ruled out significant populations in objects of lower masses. Also, Graff & Freese (1996a, 1996b) have ruled

out significant halo mass fractions in red dwarfs and brown dwarfs. Gyuk & Gates (1998) have shown that even models of rotating halos cannot lower the present experimental MACHO mass to the brown dwarf range. An increase in the average MACHO mass is however possible if more events of longer duration are detected with time. In fact, the MACHO candidate mass has increased over the last few years (Alcock et al. 1993, 1996, 1997). Therefore we have considered the possibility of MACHOs in the halo of $\sim$ solar and somewhat higher masses.

If such objects exist, they may be seen in the future by microlensing experiments as longer-timescale events. In order to have some idea of the microlensing signature of halo NSs and BHs, we derive here some rough numbers for the MACHO experiment in particular. In this work, roughly 85% of the NS/BH remnants produced have masses $\lesssim 5$ $M_{\odot}$. The duration of a microlensing event is mass-dependent; for a standard halo model, the average event timescale varies with the MACHO mass as, $< \hat{t} > \propto \sqrt{MD}/v \cong 140\sqrt{M/M_{\odot}}$ days (Alcock et al. 1997), for an assumed MACHO velocity v and distance D. Thus NSs/BHs of mass $\lesssim 5$ $M_{\odot}$, if they exist in the Galactic halo, will be picked up by the MACHO experiment as events with average timescales $\lesssim 313$ days ~ 0.86 yr. A typical NS, or a LMBH, of mass ~ 1.5 $M_{\odot}$, would have $< \hat{t} > \sim 150$ days. However, the most *probable* duration of events from 1.5 $M_{\odot}$ objects in the halo is only ~ 90 days (Griest 1991). The MACHO experiment, subsequent to the 2-year data publication, has detected a few events with durations approximately between 90 and 105 days. While this is hardly a proof of the existence of halo NSs and BHs, it is worth noting in relation to the question of how such objects would appear to microlensing experiments, and whether they may have already been detected. Given our prediction of longer timescale events from halo NSs and BHs, it is provocative that the first-year data of EROS2 in the direction of the SMC give a most probable lens mass of over 2 $M_{\odot}$ if they are present in the Galactic halo (Palanque-Delabrouille et al. 1998), though self-lensing by the SMC is also a possibility. Observations of the subsequent event SMC-98-1, however, seem to imply a binary lens located in the SMC itself (see, e.g., Afonso et al. 1998).

As the final halo mass fraction in NSs/BHs in this work is less than 100%, it is not necessarily incompatible with the presence of other components which could account for the shorter-duration microlensing events that are already detected. Obviously, one can only take the theory of two or more distinct halo populations to a point, beyond which the measured dynamical halo mass is exceeded. We have seen above an estimate of the microlensing signature from halo NSs and BHs. An alternative question is how the present microlensing data can constrain any higher-mass population. In the context of the standard halo model, the data indicate a most likely lens mass of about 0.5 $M_{\odot}$. However, the lens mass estimate depends upon the phase space distribution of the lenses within the halo. To

constrain any NS-mass population, we must explore the parameter space for galactic halo models, given the current data; we consider this problem in a subsequent work.

We gratefully acknowledge illuminating discussions with B. Holden, M. Lemoine, and F. X. Timmes, and our referee B. Fields for his many useful suggestions. We also thank E. Gates, K. Griest, A. Meiksin, M. C. Miller, and D. G. York for helpful comments. A. V. and A. V. O. were supported in part by the DOE through grant DE-FG0291 ER40606, and by the NSF through grant AST-94-20759. A. V. acknowledges the support of the Farr Fellowship at the University of Chicago.

REFERENCES

Adams, F.C. & Laughlin, G. 1996, ApJ, 468, 586

Adams, F.C. & Laughlin, G. 1997, Rev. Mod. Phys., 69, 337

Afonso, C., et al. 1998, A&A, 37, L17

Alcock, C., et al. 1993, Nature, 365, 621

Alcock, C., et al. 1996, ApJ, 461, 84

Alcock, C., et al. 1997, ApJ, 486, 697

Alcock, C., et al. 1998, ApJ, 499, L9

Bennett, D. 1998, Phys. Rept. 307, 97

Blitz, L. 1997, private communication

Brown, G.E., & Bethe, H.A. 1994, ApJ, 423, 659

Brown, G.E., Weingartner, J.C., & Wijers, R.A.M.J. 1996, ApJ, 463, 297

Burles, S. & Tytler, D. 1998, ApJ, 499, 699

Chabrier, G. & Méra, D. 1997, A&A, 328, 83

Charlot, S. & Silk, J. 1995, ApJ, 445, 124

Copi, C.J., Schramm, D.N., & Turner, M.S. 1995, Science, 267, 192

Dunn, A.M. & Laflamme, R. 1993, MNRAS, 264, 865

Elbaz, D, Arnaud, M., & Vangioni-Flam, E. 1995, A&A, 303, 345

Fields, B.D., Mathews, G.J. & Schramm, D.N. 1997, ApJ, 483, 625

Fields, B.D., Freese, K. & Graff, D.S. 1998, New Astron. 3, 347

Flynn, C., Gould, A. & Bahcall, J.N. 1996, ApJ, 466, L55

Graff, D.S. & Freese, K. 1996a, ApJ, 456, L49

Graff, D.S. & Freese, K. 1996b, ApJ, 467, L65

Graff, D.S., Laughlin, G. & Freese, K. 1998, ApJ, 499, 7

Griest, K. 1997, private communication

Griest, K. 1991, ApJ, 366, 412

Gyuk, G. & Gates, E. 1998, MNRAS, 294, 682
Heckler, A.F. & Kolb, E.W. 1996, ApJ, 472, L85
Heckman, T.M., Armus, L., & Miley, G.K. 1987, AJ, 92, 276
Henderson, A.P., Jackson, P.D., & Kerr, F.J. 1982, ApJ, 263, 116
Henry, J.P., Briel, U.G., & Nulsen, P.E.J. 1993, A&A, 271, 413
Ishimaru, Y. & Arimoto, N. 1997, PASJ, 49, 1
Kashlinsky, A., Mather, J.C., & Odenwald, S. 1996, ApJ, 473, L9
Lieu, R., et al. 1996, ApJ, 458, L5
Mihalas, D. & Binney, J. 1981, Galactic Astronomy: Structure and Kinematics [IInd ed.] (New York: Freeman and Company), Ch. 3
Mulchaey, J.S., Davis, D.S., Mushotzky, R.F. & Burstein, D. 1996, ApJ, 456, 80
Mushotzky, R.F., et al. 1996, ApJ, 466, 686
Palanque-Delabrouille, N., et al. 1998, A&A, 332, 1
Peebles, P.J.E. 1993, Principles in Physical Cosmology (Princeton University Press)
Peebles, P.J.E. 1995, ApJ, 449, 52
Puget, J.-L., et al. 1996, A&A, 308, L5
Renault, C., et al. 1997, A&A, 324, L69
Ryu, D., Olive, K. A., & Silk, J. 1990, ApJ, 353, 81
Smecker, T.A. & Wyse, R.F.G. 1991, ApJ, 372, 448
Timmes, F.X., Woosley, S.E., & Weaver, T.A. 1996, ApJ, 457, 834
Tully, R.B. 1987, ApJ, 321, 280
Tytler, D., Fan, X. -M., & Burles, S. 1996, Nature, 381, 207
Woosley, S.E. & Timmes, F.X. 1996, Nucl. Phys. A, 606, 137
Woosley, S.E. & Weaver, T.A. 1995, ApJS, 101, 181

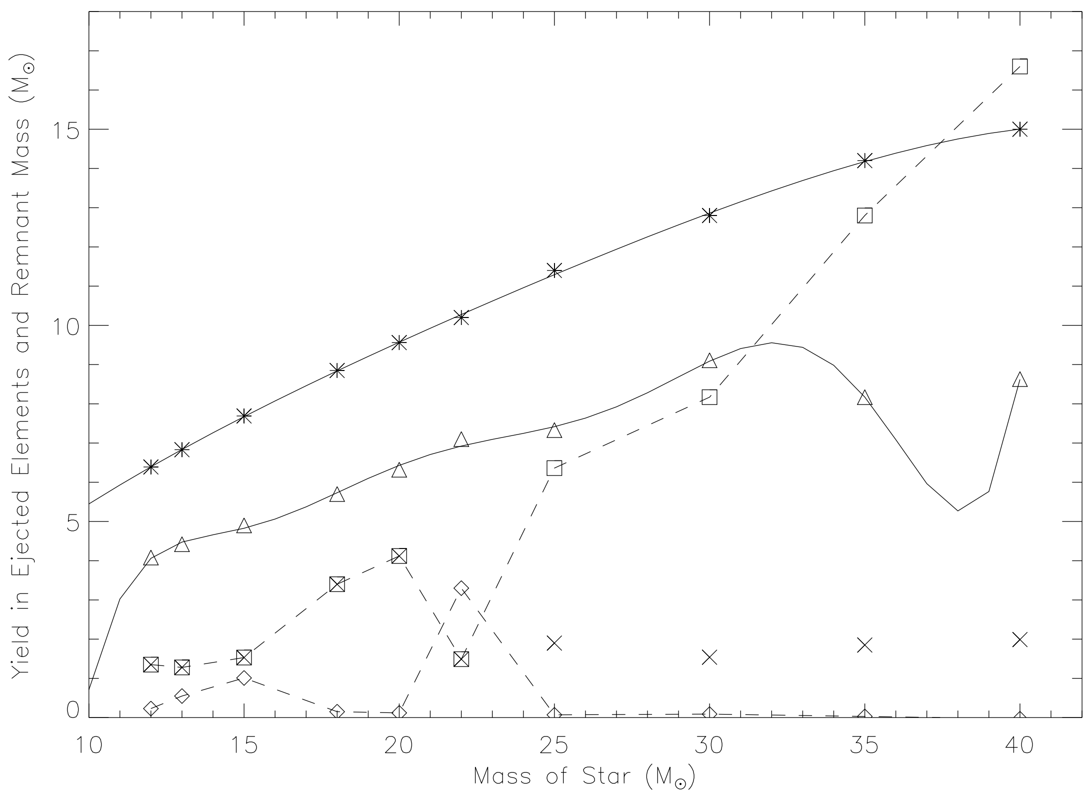

Fig. 1.— *For $Z = 0$ stars from WW95*: Ejected masses in hydrogen (plotted as asterisks), ^{4}He (triangles), and metals (diamonds). Also shown are the masses in post-supernova remnants for the minimal and maximal ejecta models (squares and crosses respectively) from WW95; the dashed lines are drawn through to guide the eye for the diamonds and squares. The solid lines, where drawn, represent the polynomial fit for that case. All quantities are in solar mass units.

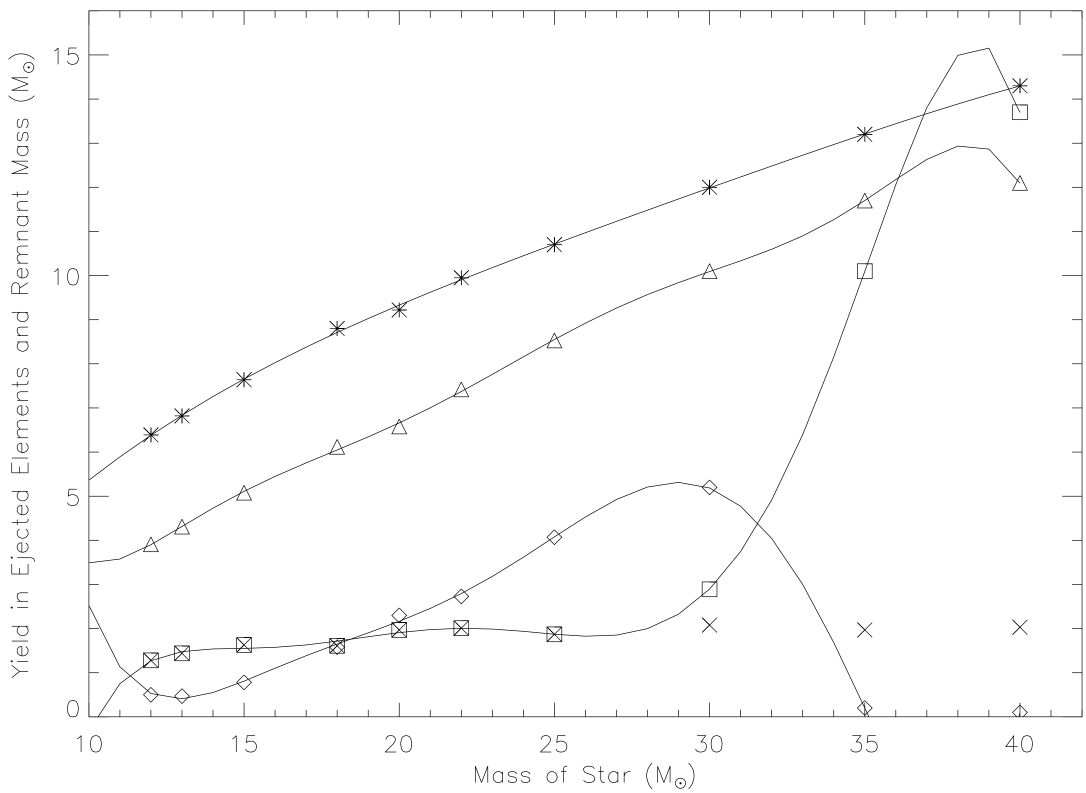

Fig. 2.— *For $Z = 10^{-4}$ $Z_\odot$ stars from WW95*: Ejected masses in hydrogen (plotted as asterisks), ^{4}He (triangles), and metals (diamonds). Also shown are the masses in post-supernova remnants for the minimal and maximal ejecta models (squares and crosses respectively) from WW95. The solid lines represent the polynomial fit for each case. All quantities are in solar mass units.

	$Z_{\rm star}$	$M_{\rm H}$ ($M_\odot$)	$M_{^4{\rm He}}$ ($M_\odot$)	$M_{\rm Z}$ ($M_\odot$)	$M_{\rm rem}$ ($M_\odot$)	f	$Y_{\rm gas}/Y_\odot$	$Z_{\rm gas}/Z_\odot$
Case 1	0	3.9×10^{11}	2.35×10^{11}	1.59×10^{10}	3.6×10^{11}	36%	1.33	1.31
Case 2	10^{-4} $Z_\odot$	3.78×10^{11}	2.77×10^{11}	6.32×10^{10}	2.89×10^{11}	29%	1.40	4.65
Case 3	$Z_\odot$ (mE)	3.35×10^{11}	2.86×10^{11}	9.76×10^{10}	2.81×10^{11}	28%	1.45	7.18
	$Z_\odot$ (ME)	3.35×10^{11}	2.86×10^{11}	1.43×10^{11}	2.36×10^{11}	24%	1.36	9.92

Table 1: For three cases of initial metallicity of the progenitor star, the yields in hydrogen, ^{4}He and metals, and remnant masses in solar mass units, from a stellar population of mass 10^{12} $M_\odot$ per galaxy. Also shown are the mass fractions of the ejected gas in ^{4}He and metals relative to solar values, and the final halo mass fraction f in remnants for a galactic halo of total mass 10^{12} $M_\odot$.

$Z_{\rm star}$	$Y_{\rm gas,i}$	$M_{\rm gas,i}/M_\odot$	$Y_{\rm gas,f}/Y_\odot$	$Z_{\rm gas,f}/Z_\odot$
0	0.232	4.7×10^{12}	1	0.42
	0.232	2.4×10^{12}	1.22	1
	0.249	6.5×10^{12}	1	0.29
	0.249	2.4×10^{12}	1.23	1
10^{-4} $Z_\odot$	0.232	5.7×10^{12}	1	1.3
	0.232	7.2×10^{12}	0.96	1
	0.249	8.1×10^{12}	1	0.89
	0.249	7.2×10^{12}	1.01	1

Table 2: For two cases of initial metallicity of the progenitor star, and two primordial ^{4}He values, the mass of initial gas required to dilute either Y or Z of the enriched ejecta from both M31 and the Galaxy to solar values, with the resulting final values in both Y and Z of the gas also shown, relative to solar values.